Device Design and Efficiency Subteam Report

Team Members

Scott Jones	Energy Conversion Devices, Inc
Robert Collins	Penn State University
Chris Wronski	Penn State University
Eric Schiff	Syracuse University
Xunming Deng	University of Toledo
Jeff Yang/Baojie Yan	United Solar Systems Corp.

Device Design and Efficiency subteam

Team priorities

Urgent Issues with highest priority

- Fabricate and improve a-Si/a-SiGe/μc-Si triple cell

- Establish device physics related to μc-Si and thin film Si

- Study the dependence of μc-Si formation on different substrates

- Evaluate and improve the doped layer in multiple junction structure for μc-Si bottom cell i-layer

- Study and control the p-i and n-i interface layers for narrow bandgap cells

- Deposition of a-SiGe and μc-Si material at high deposition rate

- Optical designs for light enhancement

- Identify and develop consensus on approaches that have the highest possibility to lead to 15% stable solar cells.
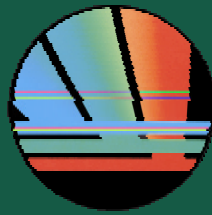
Important Issues:

- Characterization techniques for μc-Si and correlation of these measurements with device performance

- Post-deposition treatment for μc-Si solar cells

- Understanding and improving Voc

- Deposition of μc-Si in large area.
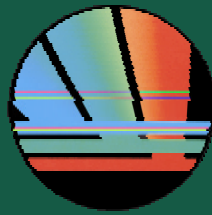
# Large-area deposition using the 30 MW/year production constrains

1. Modified the large-area deposition machine with new cathode design to simulate 30 MW/year production machine

2. Improved the uniformity over a larger area deposition (see the table below)

3. Started optimization of component and triple-junction cells using SiH_4 instead of Si_2H_6

4. Achieved an initial total-area efficiency of 10% with a-Si:H/a-SiGe:H/a-SiGe:H triple-junction structure

Average thickness uniformity data of individual layers for old and new cathodes, where Hi-Lo (%) = (maximum thickness – minimum thickness) / maximum thickness and CV (%) = standard deviation/average.

Layer	Cathode	Hi - Lo (11 x 11")	CV (11 x 11")
I1	Old	54%	22.5%
	New	**24%**	**10%**
I2	Old	46%	17.9%
	New	**23%**	**8%**
I3	Old	55%	21.3%
	New	**23%**	**8.5%**
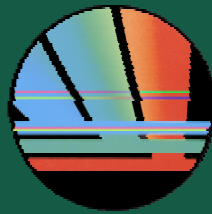
Initial total-area (0.268 cm^2) performance of component and triple-junction cells made using large-area machine after installation of new cathode. The cells were deposited with SiH$_4$ over 11" × 11" deposition area.

| Sample	Structure	Substrate	Light	P$_{max}$ (mW/cm^2)	J$_{sc}$ (mA/cm^2)	V$_{oc}$ (V)	FF
9117	top	SS	AM1.5	6.36	8.55	1.004	0.741
9179	middle	SS	>530 nm	3.45	7.42	0.678	0.687
9170	bottom	Al/ZnO	>630nm	3.08	8.14	0.595	0.635
9381	triple	Al/ZnO	AM1.5	10.0	6.40	2.242	0.704

Goal: Efficiency > 9.0% encapsulated stable large-area cell with aperture-area of 460 cm^2.
Required cell efficiency: In order to achieve this goal, we need an initial total-area (0.268 cm^2) cell efficiency > 11.2%

- **Band & bandtail parameters for a-Si solar cell models**
  - Low mobility of holes is probably a significant limitation (yesterday)
  - Measurements of V_{oc} vs. T, light-soaking (to complete parameter set)
  - Measurements of hole drift mobility (time-of-flight)
    - » What affects the hole mobility? We don't know.
    - » Fun with BP, PSU, USSC!
- **Hole mobility estimates for μc-Si**
  - Succeeding (collaboration w. Juelich)
  - Hole drift mobility around 1 cm^2/Vs at 300 K. Physics a puzzle.
- **Infrared absorption spectroscopy of interfaces**
  - Interesting, complicated spectra.
  - Not well explained by simple models for n/i and p/i interfaces. Looking at complexing & multi-phase models for doping.

First Measurement: Infrared Absorption Spectrum of *p/i* Interface in a-Si *pin* Solar Cells
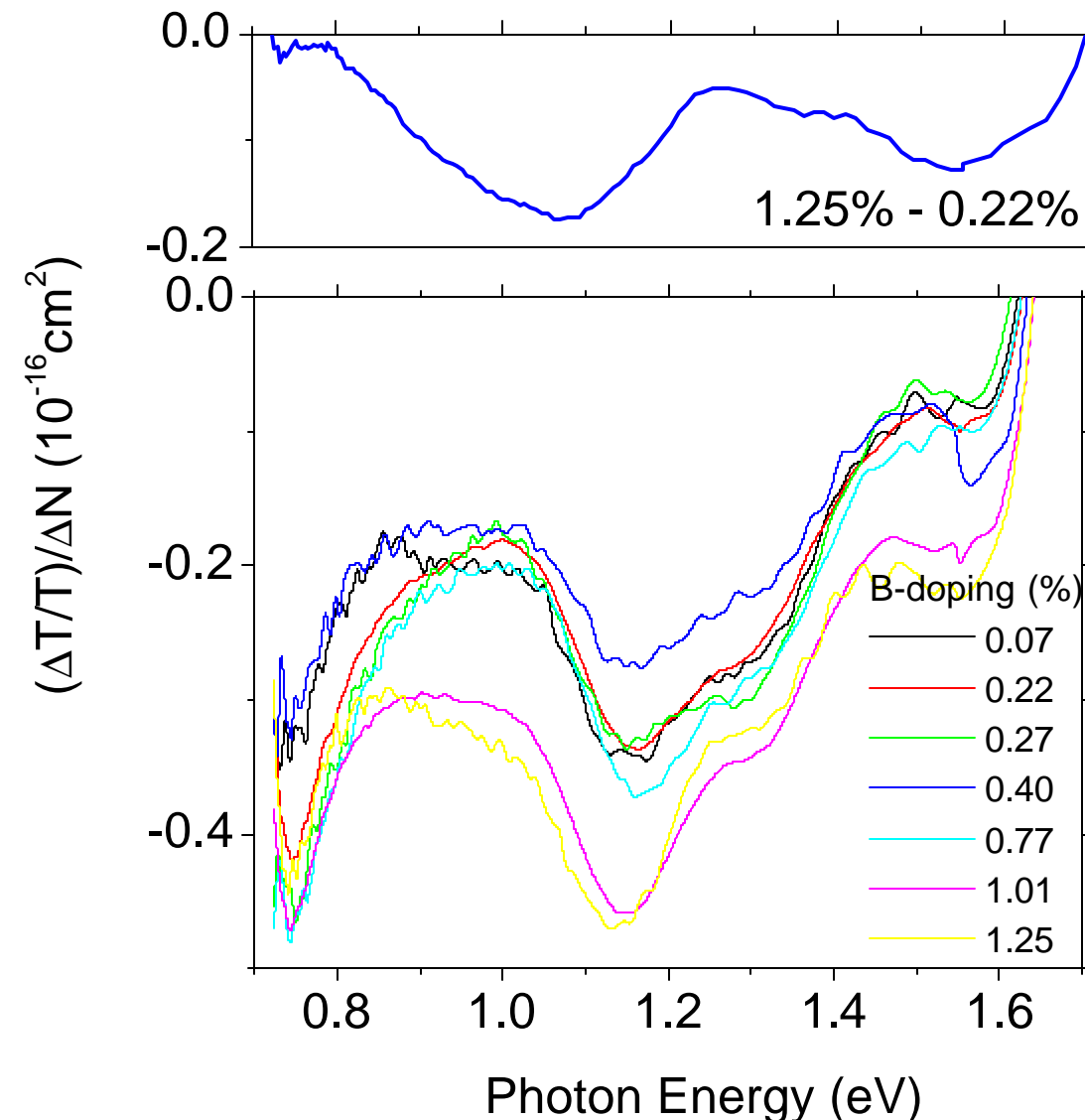

- Varying a-SiC:B p-layer sample series from BP Solar (thanks!)
- Charge modulation spectra show effect of varying B in p-layer.
  - Our grail!
- E_F shift is a partial explanation, but more structure than expected.
  - *n*-layers also full of surprises – which were likely evidence for complexing.
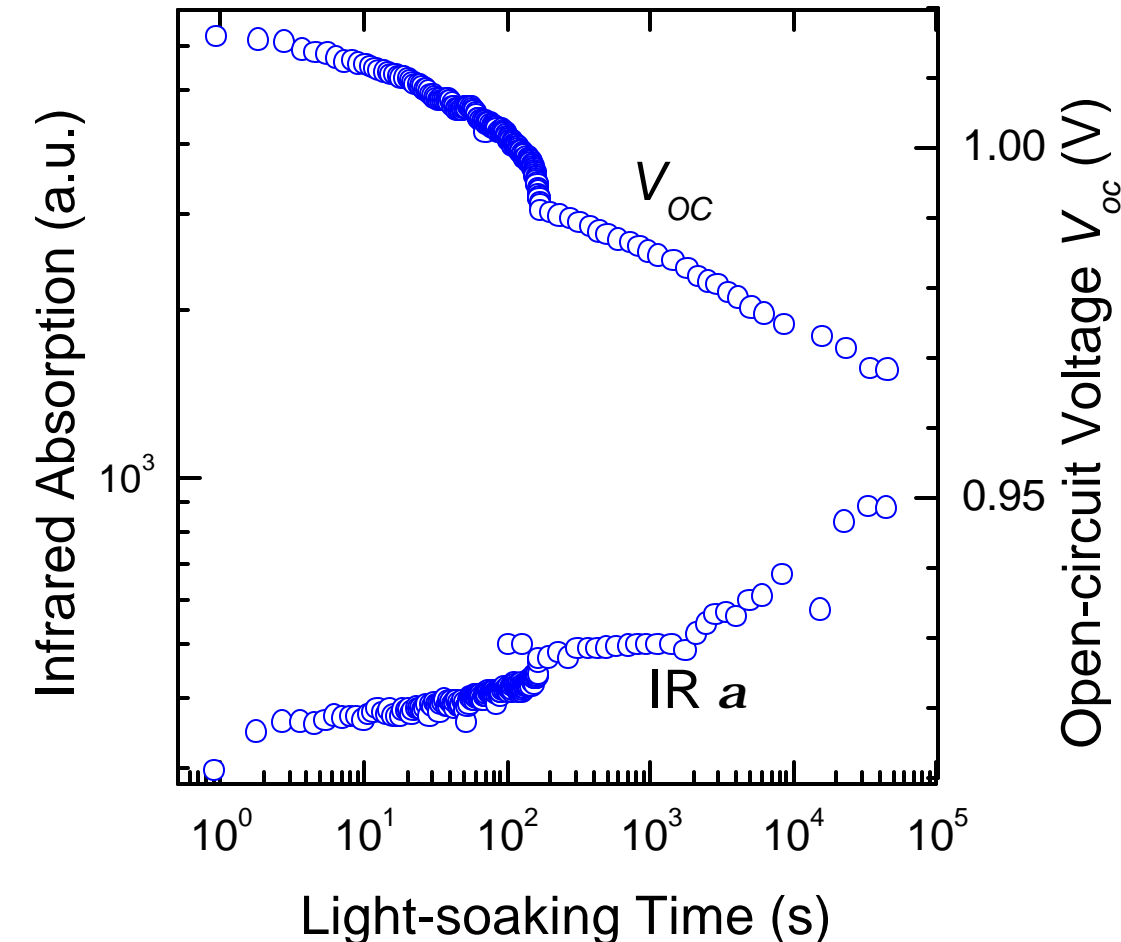
- Goal of experiment was to determine V_{OC} when $N_D = 0$ (by extrapolation).
- USSC solar cell (thanks)
- Used 1 s illumination "pulses" up to 100 s. Longer times, higher duty cycle after.
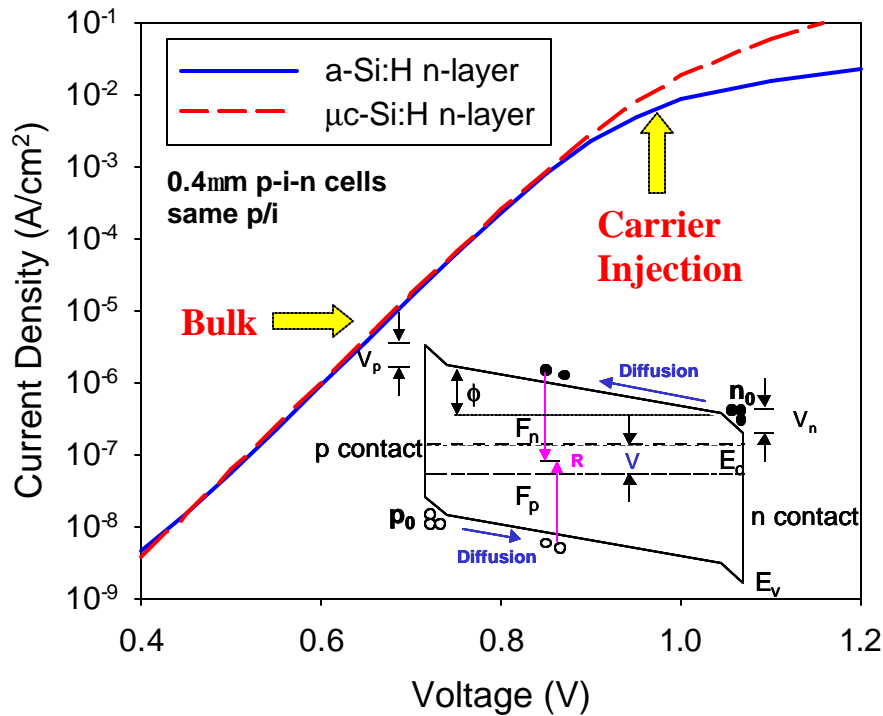- Unexplained "kink" when duty-cycle changed. Seen twice.

3
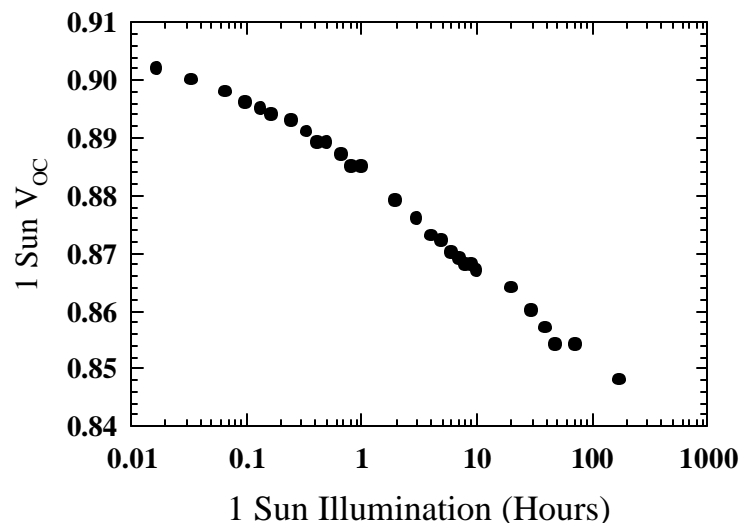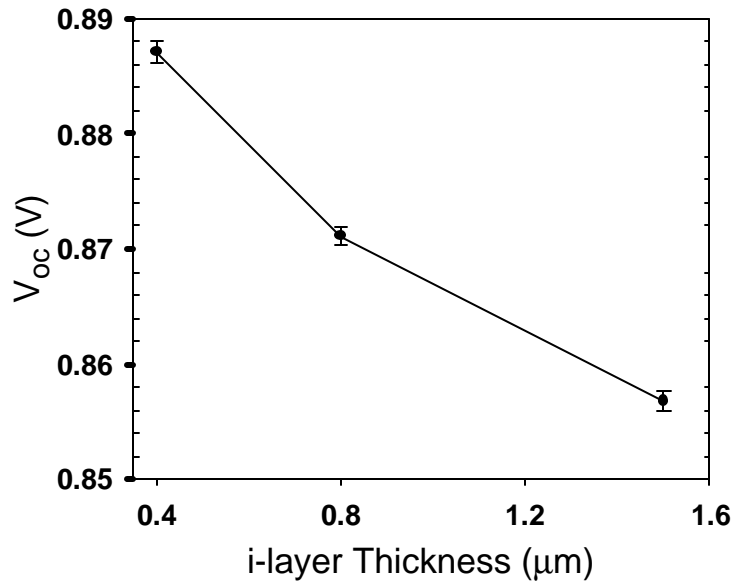
- Voltage regime over which bulk recombination dominates – limited by interface recombination.

- With optimized p/i, n/i interfaces – such transport can extend to 1 sun V$_{OC}$.

- On cells with i-layers having mobility gaps of 1.86 eV 1 sun V$_{OC}$ values limited by bulk recombination have been identified.

- Systematic increases in bulk recombination in J$_D$-V characteristics with i-layer thickness directly related to V$_{OC}$ for J$_{SC}$ of 7.5 mA/cm^2 with red light illumination.

Light induced changes in V$_{OC}$ due to SWE in bulk:
— Confirm limitations imposed by recombination in the i-layers.
— Indicate absence of limitation due to recombination through tail states – whose densities are not affected by SWE.

Importance of V_n in Determining Cell Characteristics

Current Density (A/cm²) vs Voltage (V) plot. Legend: a-Si:H n-layer (blue solid), μc-Si:H n-layer (red dashed). 0.4 mm p-i-n cells, same p/i. Labels: Bulk, Carrier Injection. Inset band diagram with p contact, n contact, V_p, V_n, ϕ, F_n, F_p, R, V, E_c, E_v, n_0, p_0, Diffusion.

- V_n: potential barrier in i-layer at n contact
- V_n determined by space charge of electron filled gap states due to large n_0 – not large densities of states.
- n_0 depends on alignment of E_F in n layer with E_c in i-layer.
- Alignment different for p-i-n cells with a-Si:H and μc-Si:H n contacts .
- Bulk recombination same.
- Carrier injection clearly lower for n-a-Si:H – higher V_n.

- **Consistent with**: close alignments of E_c, between i and n a-Si:H (E_A ~ 0.26eV); 1.1eV bandgap of μc-Si:H, ~ equal discontinuities in E_c and E_v with i a-Si:H (E_A ~ 30meV). (Koval et al., *J. Non. Cryst. Solids*, **299-302**, 1136, 2002)
- **Opposite** conclusion by Poissant et al. (*J. Appl. Phys*. **93**, 170, 2003) based purely on V_{OC} and modeling results.
- No effect on V_{OC} – zero current flow.

Device Design and Efficiency Research

University of Toledo

- To study the effect of interface layers at ITO-p and n-ZnO. Need to deposit 12 layers of triple cell without vacuum break

- A new self-designed 5-chamber system (four sputter + one loading) to allow uniform deposition of 4"x4" films (Ag, Al, ZnO, ITO) is being integrated into UT's existing 4-chamber PECVD/HWCVD system. Project 70% completed.

- One sputter chamber is completed. Uniform deposition achieved using a rotating substrate holder over a 3" sputter target. ITO film is being optimized in this chamber.
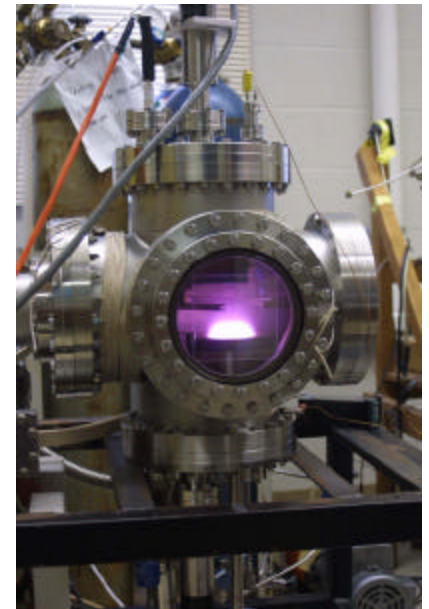
Improved back reflectors using multi-layer approach

Energy Conversion Devices, Inc.
Greg Demaggio, Scott J. Jones (P.I.) Tongyu Liu, Jeff Steel and David Tsu

Goal: Devise new multi-layered back reflector that will lead to enhanced cell currents and improved efficiencies.

First Approach: Take present Al/ZnO back reflector used in production and add optical stack of materials with different indices for refraction. In particular, add layers with high n to enhance reflection in the >600nm region.

ZnO
Al

_____

ZnO
Multi-layer stack
Al
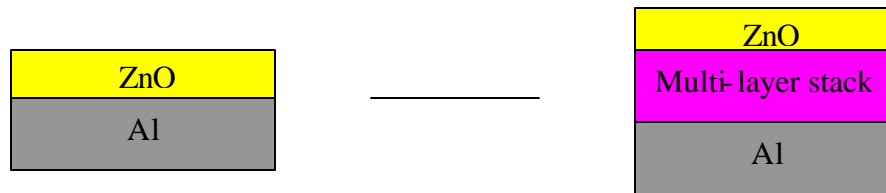
Activities:
Focusing on multi-layer structure of (low n)/(high n)/(low n) materials
With high n material being Si and low n material being ZnO alloyed with elements identified as X and Y
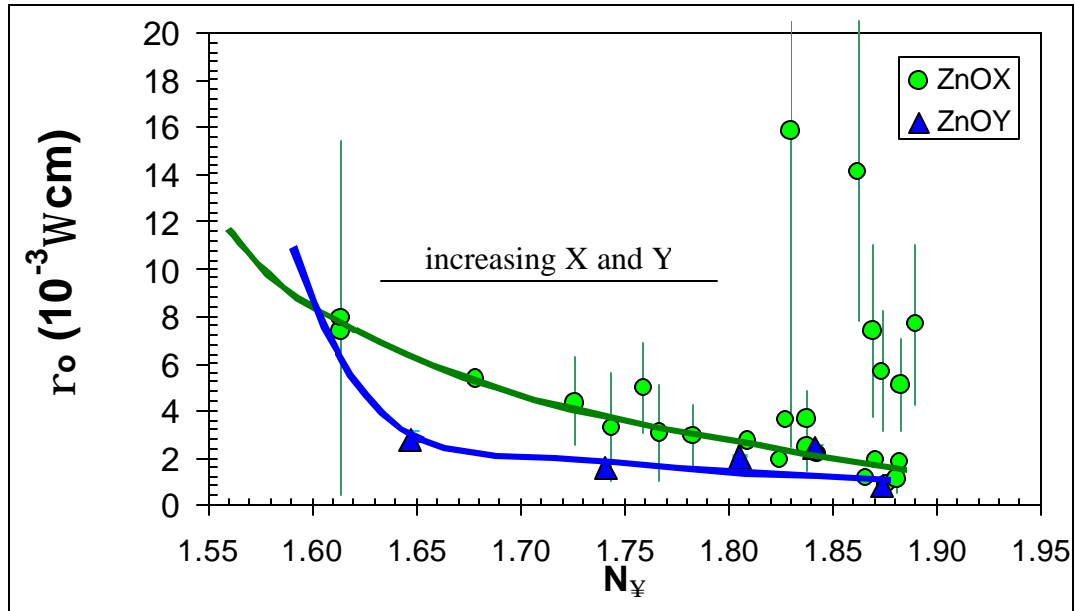
ZnOX
Doped Si
ZnOX

Using dc sputtering to fabricate layers

Most of our work has been on producing the ZnO alloys to prepare materials with:
1) High transparency
2) High conductivity
3) Low n (below 1.7)

Through alloying with X and Y, have been able to prepare materials with high conductivity ($\rho_o < 10^{-3}$ Ωcm), high transparency (96-97%) and n between 1.6 and 1.7.

Initial Cell Performance **without optimization of layer thicknesses** demonstrates similar Voc, FF and R_s for cells with Ag/ZnO and new back reflector materials – Currents need to be improved with proper optimization of back reflector film thicknesses.

| Back reflector	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	R_s (Ω cm)	P_{max} (mW/cm^2)
Ag/ZnO	0.641	22.68	0.497	8.7	7.23
Al with ZnOX	0.638	19.18	0.496	9.9	6.06
Al with ZnOY	0.639	20.60	0.494	9.6	6.50

DEVICE DESIGN AND EFFICIENCY
OPTICALLY-BASED LIMITATIONS TO EFFICIENCY

Goal: A basic understanding of the optical physics of solar cells, verified through experimentation, that allows separation, quantification, and ultimately -- though simulation -- prediction of the optically-based limitations to solar cell efficiency

New results: Advanced TCO measurement capabilities.
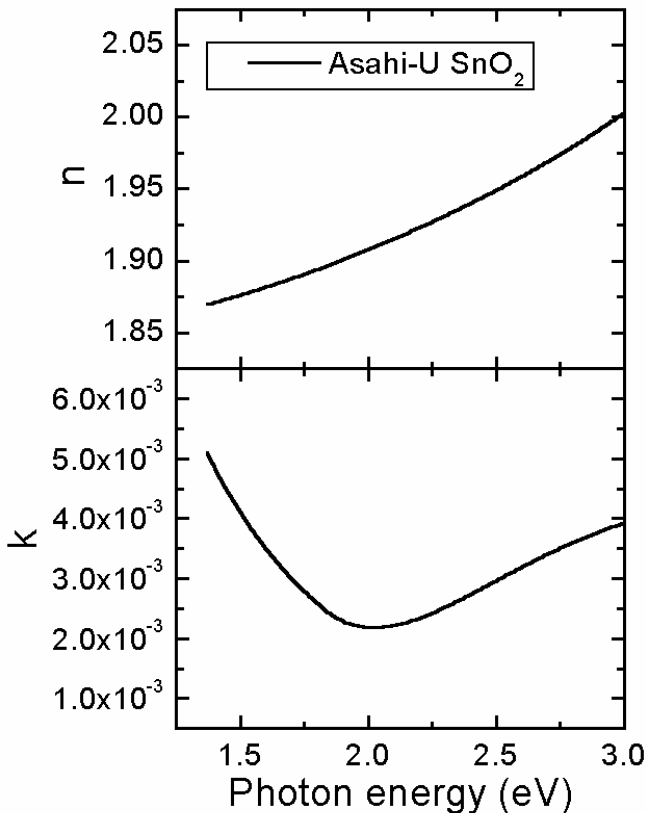
Determination of optical properties and structure of materials in the textured state through*:

(i)   better suppression of scattering via two-layer sandwich contacted with index-matching fluid

(ii) improved separation of the absorption due to TCO and glass

(iii) more advanced optical modeling that combines SE on textured surface (for n) and T on index-matched sandwich (for k)

* G. M. Ferreira et al., MRS Proc. (2003, in press)
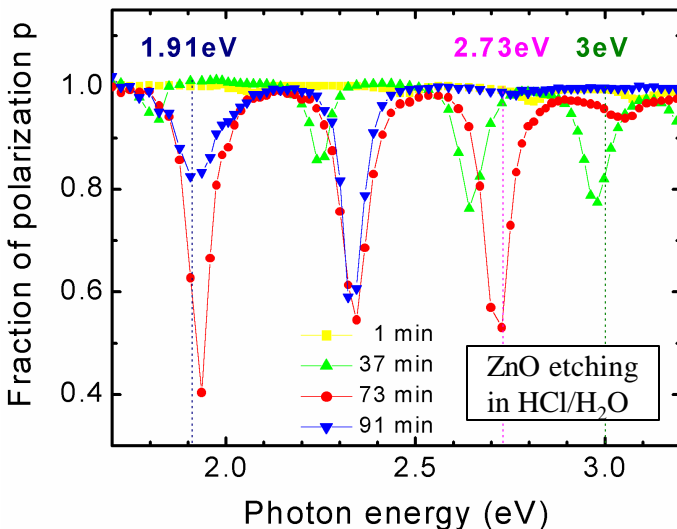
Real time characterization of optical properties and *structural evolution* by "Mueller matrix ellipsometry"*:

(i)   "microscopic scale" roughness from polarization change upon reflection

(ii) "macroscopic scale" roughness from reflectance deficit

(iii) "geometric scale" roughness from the degree of polarization

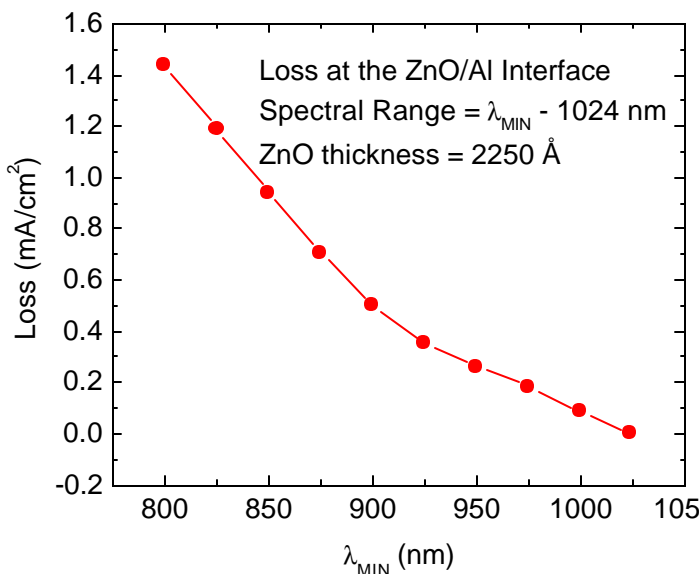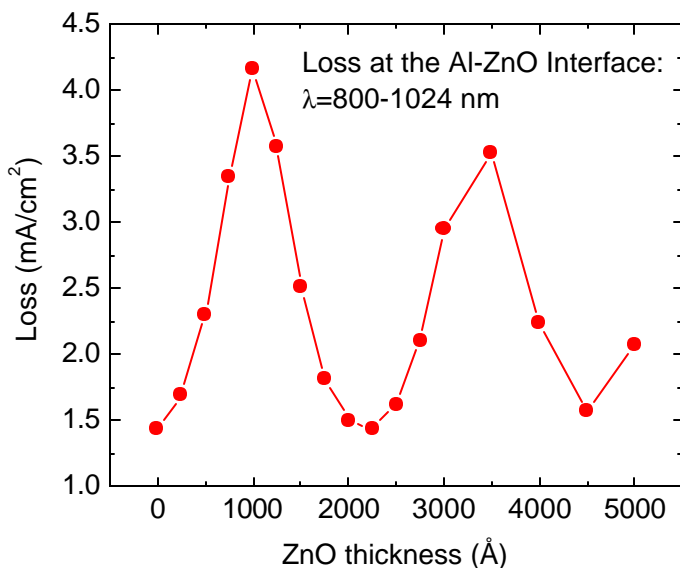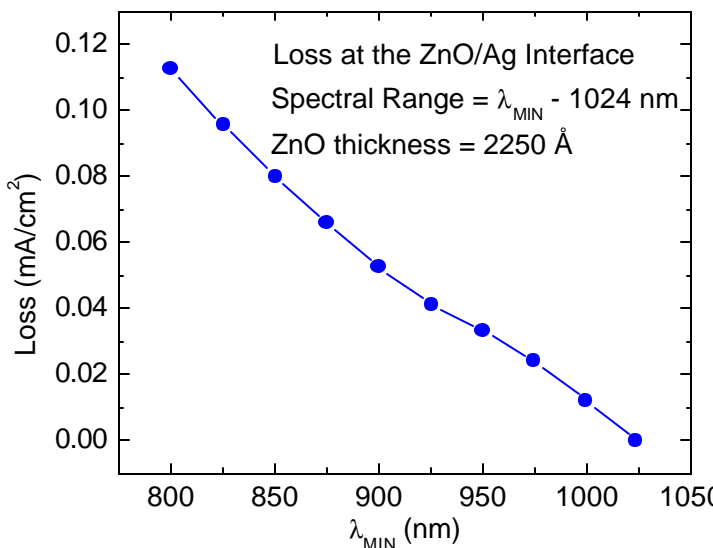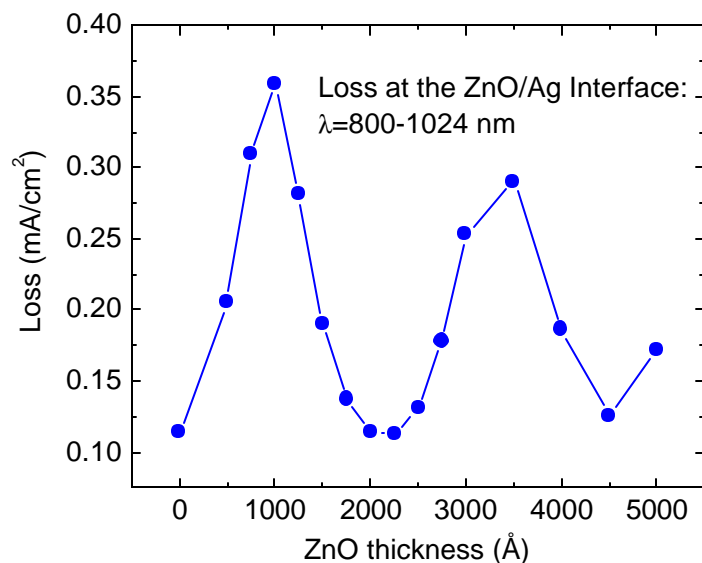* C. Chen, et al., Phys. Rev. Lett. **90**, 217402 (2003).

DEVICE DESIGN AND EFFICIENCY
OPTICALLY-BASED LIMITATIONS TO EFFICIENCY

Goal: Multilayer transparent conductors to minimize high energy reflection and parasitic absorption losses

Approach: Need a multilayer broad-band anti-reflector (400 - 800 nm) as a top contact; also need a multilayer broad band "perfect" reflector (800 - 1000 nm) as dielectric spacer in retroreflector

Example of losses that must be overcome with this approach; ΔJ_{sc} obtained by integrating the absorption loss over the range from λ_{min} = 800 nm to λ_{max} = 1024 nm

Loss at the ZnO/Ag Interface: λ=800-1024 nm

Loss at the ZnO/Ag Interface
Spectral Range = λ_{MIN} - 1024 nm
ZnO thickness = 2250 Å

Loss at the Al-ZnO Interface: λ=800-1024 nm

Loss at the ZnO/Al Interface
Spectral Range = λ_{MIN} - 1024 nm
ZnO thickness = 2250 Å

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- Establish device physics related to µc-Si and thin film Si **(SU)**

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- Evaluate and improve the doped layer in multiple junction structure for µc-Si bottom cell i-layer **(USSC)**

- Study and control the p-i and n-i interface layers for narrow bandgap cells **(USSC, UT)**

- Deposition of a-SiGe and µc-Si material at high deposition rate **(USSC, ECD, UT, PSU)**

- Optical designs for light enhancement **(ECD, UT, PSU)**

- Identify and develop consensus on approaches that have the highest possibility to lead to 15% stable solar cells. **(USSC)**

Important Issues:

- Characterization techniques for µc-Si and correlation of these measurements with device performance **(SU, UT)**

- Post-deposition treatment for µc-Si solar cells

- Understanding and improving Voc **(USSC, SU)**

- Deposition of µc-Si in large area. **(USSC)**

Future Plans

United Solar:

- Continue to optimize μc-Si materials and cells to be integrated into a-Si/a-SiGe/μc-Si triple-junction structure. a-Si top and a-SiGe will also be optimized

- Continue to optimize large area a-Si/a-SiGe/a-SiGe structure using constraints imposed by production conditions.

ECD:

- Develop optically enhanced back reflector

- Develop high rate μc-Si deposition process

Future Plans—Con'd

Syracuse:

- Conduct hole mobility measurement for dilution series, dep-rate series, CIS

- Polymer/Si heterojunctions

- IR spectroscopy (interfaces, μc-Si)

- Device physics and modeling $\rightarrow$ degraded state

PSU—Wronski:

- Continue research in present areas.

Future Plans—Con'd

Collins (PSU and UT):

- Optimization of optical collection—expt.

  - Grading schemes in SiGe:H (UT)

  - Texturing of back-reflector ZnO (PSU)

  - Index variation in ITO and ZnO (UT)

  - Improved ZnO/metal interfaces

- Optimization of Optical Collection—Theory

  - Optical function of material components

  - Properties of interfaces

  - Micro/macro/geo roughness

Future Plans—Con'd

Collins (PSU and UT):

- Materials—Phase diagrams and protocrystalline SiGe:H

    - RF and VHF PECVD with SiH4/GeH4 (PSU)

    - RF and VHF PECVD with Si2H6/GeH4 (UT)

- Materials—Phase diagrams and optimization of uc-Si:H

    - RF, VHF, HWCVD (UT)

Deng (UT)

- Deposit complete ITO/a-Si/a-SiGe/a-SiGe/Al/ZnO in an integrated system without vacuum break

- Deposit μc-Si solar cells using VHF PECVD and HWCVD